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Award Number: W81XWH-05-1-0335

TITLE: EcoHealth Consortium Workshop on Emerging Infectious Diseases and Information Technology

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REPORT DATE: October 2005

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE 01-10-2005	**2. REPORT TYPE** Final	**3. DATES COVERED** 1 Mar 2005 – 30 Sep 2005

4. TITLE AND SUBTITLE

EcoHealth Consortium Workshop on Emerging Infectious Diseases and Information Technology

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-05-1-0335

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Bruce A. Wilcox, Ph.D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Hawaii
Honolulu, HI 96822

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

During March 9-11, 2005, a meeting was convened by the East West Center and the Asia-Pacific Institute of Tropical Medicine and Infectious Diseases at the University of Hawaii as part of National Institutes of Health Roadmap initiative ‘‘Research Teams of the Future’’. The meeting was entitled Emerging Infectious Diseases and Social-Ecological Systems. The purpose of this meeting was to advance interdisciplinary methods for investigation of the problem of emerging infectious diseases. While the meeting focused primarily on conceptual integration, employing a holistic systems perspective based on the emerging paradigms employing complexity theory, a parallel workshop was held on the applications of remote sensing, GIS, and environmental sensing technology. This document summarizes the results of the meeting and workshop, including the post-meeting synthesis, as they relate to environmental sensing technology and the potential applications to biosecurity.

15. SUBJECT TERMS
NOT PROVIDED

16. SECURITY CLASSIFICATION OF:				**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** USAMRMC
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	10	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Integrating Sensor Technology and EID Science for Biosecurity Applications

Summary Report and Synthesis of the Results of the Meeting on Social-Ecological Systems and Emerging Infectious Diseases with Special Reference to Biosecurity Applications

Bruce Wilcox[1], Kristin Duin[2] and Andrew Hood[2]

Background

During March 9-11, 2005, a meeting was convened by the East West Center and the Asia-Pacific Institute of Tropical Medicine and Infectious Diseases at the University of Hawaii as part of National Institutes of Health Roadmap initiative ‘‘Research Teams of the Future’’. The meeting was entitled Emerging Infectious Diseases and Social-Ecological Systems. The purpose of this meeting was to advance interdisciplinary methods for investigation of the problem of emerging infectious diseases. While the meeting focused primarily on conceptual integration, employing a holistic systems perspective based on the emerging paradigms employing complexity theory, a parallel workshop was held on the applications of remote sensing, GIS, and environmental sensing technology. This document summarizes the results of the meeting and workshop, including the post-meeting synthesis, as they relate to environmental sensing technology and the potential applications to biosecurity.

Scope of the Problem of Emerging Infectious Diseases

Emerging infectious diseases (EID) are diseases that have recently increased in incidence or in geographic or host range (e.g., tuberculosis, cholera, malaria, dengue fever, Japanese encephalitis, West Nile fever, and yellow fever), diseases caused by new variants assigned to known pathogens (e.g., HIV, new strains of influenza virus, SARS, drug resistant strains of bacteria, Nipah virus, Ebola virus, hantavirus pulmonary syndrome, and avian influenza virus), and bacteria newly resistant to antibiotics, notably the multiple antimicrobial resistant strains. The approximately 100 pathogens classified as EID since the Centers for Disease Control and the World Health Organization began reporting such diseases are believed to have resulted from ‘natural’ and ‘accidental’ human-induced processes or events. However, this does not lessen their threat to our national security; the same mechanisms and modes of pathogen transmission, spread and even release are relevant to prevention, monitoring and surveillance in warfare or terrorist situations. Nearly all of the high priority pathogens from a disease and national security risk currently are or originated as zoonotic diseases, thus are (or are capable of) being maintained, adapting (including acquiring increased virulence), and spreading in the environment. EIDs are in fact a consequence of the systemic properties of environmental systems – biologists view pathogens as a normal component of natural ecosystems – and they can be described as simply an emerging property. Three kinds of environmental systems of particular relevance to EIDs can be distinguished:

- Natural environmental systems (natural and human modified landscapes)
- Human-built environmental systems (municipal, industrial, and agriculture water systems)
- Combined human-natural systems (agriculture production and food distribution systems)

The factors identified as responsible for re-emerging and emerging infectious diseases involve mechanisms operating on the molecular level (pathogen adaptation) to the level of regional environmental systems (demographic and land use change) and beyond (global change). Moreover, the factors believed

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responsible for the most significant new disease threats (HIV/AIDS, SARS, Ebola, West Nile virus, etc.) and re-emerging diseases (malaria, dengue, leptospirosis, plague, etc.) are associated with natural environmental systems.

By contrast, the built environment includes engineered or constructed systems (municipal water, food distribution, or mass transit systems) that can facilitate inadvertent or planned modalities for pathogen transmission. Intensified livestock or animal production systems (e.g., 'factory farming' or simply high density animal production systems), which are an important source of new pathogens, particularly, antimicrobial resistant strains [e.g., methicillin resistant *Staphylococcus aureus* (MSRA), E.coli 0:157], can be viewed as a hybrid of natural and human built systems.

The same can be said for traditional, intensified farming and food production systems, such as seen in rural China where farming families, swine, and poultry live in close quarters or where wild caught animals or their products are brought into the markets where they are brought into contact with other wild and domestic animals. The viruses responsible for influenza and SARS emerged from such systems.

Each of these categories of systems warrants attention using monitoring and surveillance methods. The monitoring and surveillance can be conducted for the basic research needed to elucidate mechanisms involved in disease emergence as a basis for developing prevention and control strategies. Instruments can be deployed to remotely monitor environmental systems, and reservoir hosts of vectors or human populations can be monitored for pathogens directly using sentinels (animals) or clinical data (humans).

Relevance of Sensor Technology and EID Research to Biosecurity

The point of this brief assessment is to address the potential applications of sensor technology deployed in the environmental systems as described above. Sensor technology refers to equipment used to detect variables contained in environmental media such as soil, water and air; data loggers and radio transmitters to store and stream sensed data; and a database system to organize and analyze the data. Cumulatively the equipment and technology infrastructure comprise what is herein refereed to as the environmental sensing network. In theory this environmental sensing network includes so-called 'biosensors' designed to detect pathogens in environmental media. Biosensors have been developed and used in laboratory and other controlled settings requiring technicians to prepare and conduct bioassays and analysis. However, biosensors capable of detecting specific pathogens in unattended, remotely deployed locations under continuous sampling regimes have not yet been developed. Currently it is not known whether such devices could be deployed in a field setting as relatively easily and inexpensively as those used for detection and measurement of physicochemical variables such as temperature, pH or salinity.

This report focuses on the potential of environmental sensing networks capable of collecting and transmitting real time data from proven and commercially available environmental sensors, whose construction and deployment recently has been demonstrated. The application potential of such systems in the context of biosecurity is two-fold:

1) For basic research on the complex ecological mechanisms and dynamics of environmental systems, including those involving host reservoir and vector populations and their pathogens, responsible for the transmission dynamics that underlie disease emergence.

2) For electronic surveillance systems capable of providing early warning of environmental indicators associated with disease emergence.

Environmental system monitoring and surveillance is an essential component of a biosecurity program: from an R&D standpoint in terms of model development; and, from prevention and preparedness standpoints in terms of prediction, surveillance, prevention and event response. There are three types of circumstances which pose a potentially significant health risk to the general public, health care workers and other first responders, and/or strategically or tactically deployed military personnel. Each applies whether pathogens are of natural or human origin (i.e., genetically modified by or released into the environment by humans, or both).

1. Pathogen invasion – Inadvertent or malicious introduction of exotic pathogens (or exotic variants or genetic material of pathogens) into the environment that are capable of infecting animal (or plant) hosts which can serve as continuous (enzootic) reservoirs;

2. Infected vector or host introduction – Use of animal vectors or hosts (released into the environment) to introduce or spread a pathogen thus create disease sources; and,

3. Environmental change induced disease emergence – Natural or human caused (inadvertent or malicious) resulting in changes in pathogen life cycle, and spatial or temporal shifts in host/vector populations.

How these 'disturbances' can lead to disease emergence in terms of the mechanisms involved, and how the research and pathogen containment/disease control problem is potentially resolvable with the application of sensor technology is described below. This discussion draws largely from the articles published in the special issue of ***EcoHealth***, Volume 2, Issue 4 (December 2005), developed on the basis of the March 2005 meeting on Social-Ecological Systems and Emerging Infectious Diseases.

Environmental Systems Vulnerability to Pathogen Emergence

The recent introduction and spread of West Nile Virus (WNV) in the U.S. provides an excellent case demonstration of our country's vulnerability to novel zoonotic infectious diseases. WNV expanded from a single entry point (the result of a single infected bird, or a human or mosquito arriving on a flight from Israel) in the Bronx or Long Island (New York). From this point it spread across the continent at the rate of about 1000 km per year. The WNV case illustrates the role of 'natural' reservoirs and 'herd' immunity, the latter lacking among North America's wild and domestic fauna (and people). The mosquito borne virus infected a wide range of animals, killing large numbers of birds, but in the process, created a wild reservoir for the disease. This reservoir is now represented by a variety of America's native (and introduced) vertebrate and mosquito species. WNV can now be described as endemic to North America and outbreaks and epidemics can be expected to persist indefinitely.

The case of WNV shows how vulnerable we are to a maliciously introduced pathogen. A much more virulent pathogen could be developed and introduced using natural hosts or vectors in basically exactly the same way. In fact, right now there is little or nothing we could do outside of clinical interventions to prevent the spread of an introduction of this or the H1N5 strain of the influenza virus (i.e. bird flu) via natural hosts. However, an improved understanding of the role of the environment and natural reservoirs and vectors in pathogen transmission would significantly enhance our early warning system and reduce disease risk. Sensor networks linked with satellite remote sensing could dramatically improve the precision of predictive models linking reservoir and vector presence or abundance to environmental factors varying in space and time. This potential is made apparent in the case of cholera described below.

Sensing technology has the potential to monitor actual or potential reservoir or vector abundance and distribution, environmental factors determining their distributions, and the use of monitoring as a basis for integrated, adaptive reservoir/vector control regimes. All environmental systems, whether urban, peri-urban, or rural, support 'ecological communities' including vertebrate and invertebrate populations capable of serving as hosts or vectors of human pathogens. A given system also has a characteristic ‘profile’ of environmental media (soil, air, and water) as well as ‘habitat’ of varying degrees of suitability for pathogen (if it has a free-living stage) hosts and vectors, that ultimately determine pathogen transmission dynamics. This determines the speed of pathogen transmission, whether it can be contained, and how a disease outbreak can be controlled at its source. Even in the case of relatively well-studied hosts or vectors, such as the mosquito *Aedes egypti* vector for dengue, the abundance and distribution of the vector, and the variability in temporal distribution in dengue endemic areas is poorly known. However, the potential for understanding these dynamics for both vector borne and water borne pathogens is greatly enhanced with the new environmental sensor technology. Here we briefly describe in more detail how, by building on existing knowledge of pathogen biology and disease ecology from EID research, sensors could be deployed to refine models of disease emergence which, combined with sensors deployed accordingly, represent significant potential for biosecurity applications.

Vector borne pathogens. Previous and ongoing research indicates meteorological and microhabitat conditions can be used to predict vector and reservoir abundance reasonably well in a number of circumstances. High resolution satellite imagery has shown potential in this regard, although the availability of ‘ground truthed’ data of high spatial and temporal resolution has limited the accuracy of predictive models. A sensor network, in which placement of individual sensors is guided by a priori knowledge or working models of host, vector, or pathogen ecology, would substantially improve the basic research as well as monitoring capacity in conjunction (and possibly independently of satellite remote sensing in some cases). Simple spatial comparison of the meteorological requirement of the habitat of the tick *Isodes scapularis*, the vector of pathogen causing Lyme disease, and the tick’s known geographic distribution demonstrates the power of such data, even without the benefit of real-time, ground-based sensors (see Figure 1 Brownstein et al., 2004).

Waterborne pathogens. One of the world’s most well-studied pathogens and diseases, *Vibrio cholerae* and cholera, provides possibly the best example of the potential of sensors both in disease research and early warning surveillance systems. A time series comparison of predicted and observed cholera incidence in Matlab, Bangladesh, 1998–2002 is shown in Figure 1 (Wilcox and Colwell 2005; Based on Calkin and Colwell [unpublished data]). Predicted cholera rates are calculated based on sea surface temperature and sea surface height data measured by satellite remote sensing data, and chlorophyll. Cholera incidence rate is actual incidence. The next step in this field, besides the development of a model with this level of precision for a vector borne disease, is to add a spatial component.

Another advance in understanding disease emergence, which was presented for the first time at the Honolulu meeting, involves higher order environmental effects, based on the interaction between land use/cover change and climate. Rapid and unplanned urbanization, agriculture intensification, and natural habitat destruction/alteration are suspected of influencing disease emergence in this way. One set of factors known to have this influence is reservoir host infection prevalence and pathogen transmission dynamics for waterborne disease (e.g., cholera, norovirus, campylobacter, and leptospirosis) involves the surface hydrology of watersheds or drainage basins. The watershed model based on ecosystem resilience Wilcox (in prep) (see Figure 3 Kaneshiro et al. 2005, also Vinetz et al., 2005) explains how unplanned urban development increases the risk of disease emergence in the case of leptospirosis. This most common and widely distributed zoonotic, water borne disease has a prevalence in Hawaii that is 30 times higher than reported for the continental U.S. The development and ecological degradation of Hawaii’s so-called ‘mountain-to-sea ecosystems’ appears to be a major factor in this disease’s emergence in Hawaii.

Hawaii’s so-called ‘mountain-to-sea ecosystems’ (described in Kaneshiro et al., 2005) can be seen as microcosms of large scale regional systems undergoing similar environmental changes with associated cases of disease emergence throughout the world’s coastal regions. As is being attempted in several study sites in Hawaii, sensors networks could be deployed to predict the effects of development-associated changes in watershed/drainage basin parameters on floods and drought conditions, and host reservoir infection prevalence. This would provide a basis for monitoring and adaptive disease management based on integrated landscape and storm drainage system design and management, in conjunction with host reservoir population control. This application of sensor networks, together with land use/cover data, could be used to parameterize hydrological models. In addition to flow data, water quality data can be useful in calibrating these models and monitoring conditions associated with reservoir or pathogen abundance.

Environmental Change and Disease Emergence

As suggested by the work on cholera, and illustrated in Figure 1 in Wilcox and Colwell, and their EID blueprint (2005, Figure 2), numerous environmental factors influence disease emergence. Lapses in public health measures, regional environmental change, and climate all have been described by different experts, specifically as drivers of infectious disease emergence. In fact, factors related to public health infrastructure, regional environmental change, and climate strongly interact in complicated ways that remain poorly understood. However, focusing on land use/cover change and climate in particular, the picture of how some of these factors interact to facilitate disease emergence is becoming increasingly clear. Sensor systems have significant potential to provide data necessary to develop predictive models and early warning systems on this basis. What has become most clear is that environmental variability, including what ecologists refer to as 'ecosystem disturbance', plays a critical role in disease emergence. This role has been demonstrated in terms of seasonal variation, as seen in for the case of the monsoon and dry season effects on cholera outbreaks. It also has been demonstrated in the case of variation on the decadal time scale, such as in the case of El Niño Southern Oscillation (ENSO) and its affect on cholera, hanta infections, and other reservoir or vector born diseases. Finally, the change in global climate now underway represents yet another level of interaction, whose complexity is represented by the hierarchical structure and cross-scale influences characteristic of environmental systems (see Figure 3 in Wilcox and Colwell, 2005).

Conclusion

Whether a particular environmental system (e.g., a city) is vulnerable to the intentional or unintentional introduction of pathogen with epidemic consequences (such consequences could be immediate or involve a latency period) is potentially understandable using existing environmental (including hydrological and climate) models and drawing on ecological theory. Environmental sensor networks provide a potentially powerful adjunct to laboratory and field research and satellite remote sensing technology, as a basis for early warning monitoring systems of disease emergence risk. Risk characterization, possibly using this combination of sensor technology and EID research, could produce reliable, rationally-based 'signals' indicating qualitative risk levels (i.e., high, medium, low). Such a system could be integrated with animal and human pathogen/disease surveillance to create an integrated EID research, monitoring, and early warning systems. Such systems could provide the basis for mitigation of system vulnerability, from both the standpoints of inadvertent disease emergence events and bioterrorism.

Off-the-shelf equipment and proprietary data logging software that have been combined to take advantage of available radio frequencies and the internet, and a GIS platform represent an important advance as a basis for environmental monitoring and surveillance. The capability of fitting the data logger/transmitter with available environmental sensors for standard physicochemical variables and to deploy a sensor network in nearly any terrain represents a significant opportunity to establish monitoring and surveillance systems with significant biosecurity. However, a significant challenge to the deployment sensor systems capable of gathering and analyzing meaningful information will require closer collaboration of sensor engineers, GIS/remote sensing specialists, modelers, and biostatisticians, and experts from other disciplines in the environmental and ecological sciences.

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